

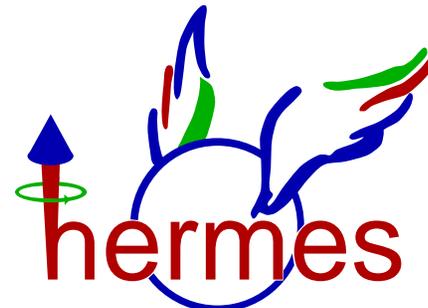
Measurements of Quark Hadronization in a Nuclear Environment

Ed Kinney

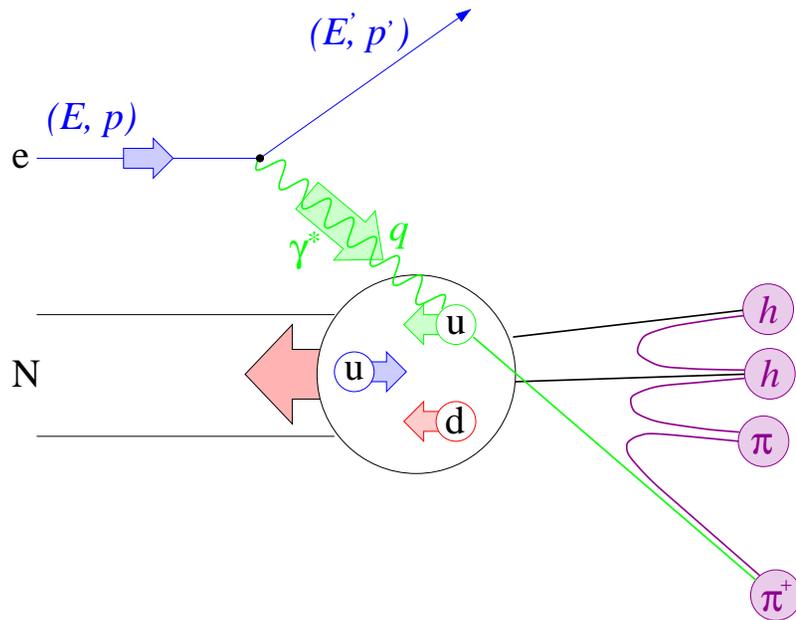
University of Colorado at Boulder

21st Workshop on Nuclear Dynamics

5-12 February 2005



Semi-inclusive Hadron Production

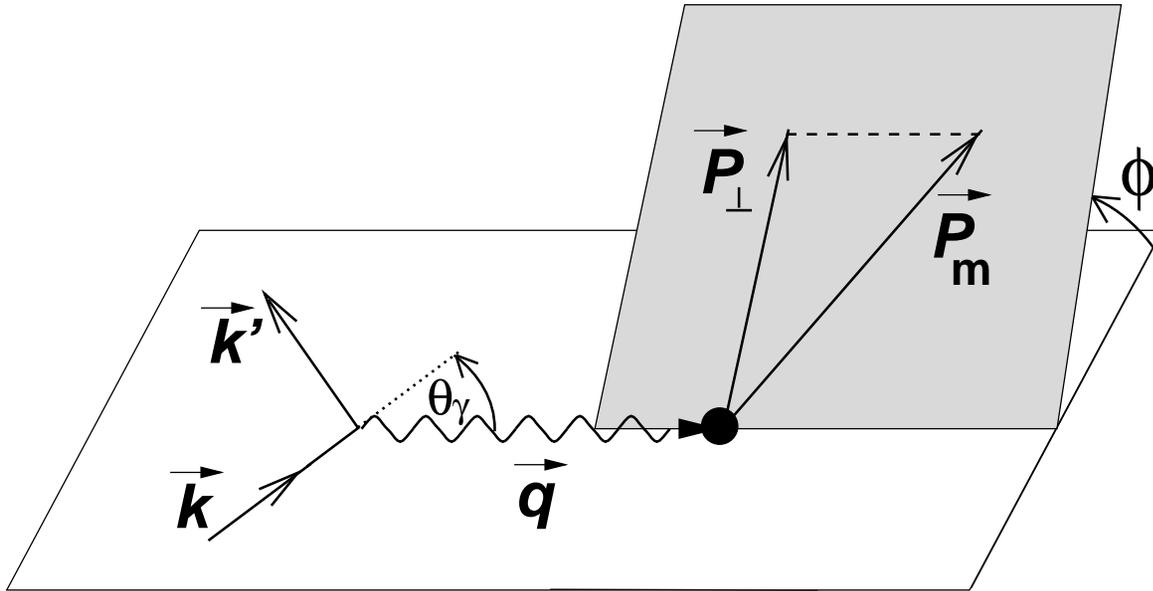


- Semi-inclusive cross section:

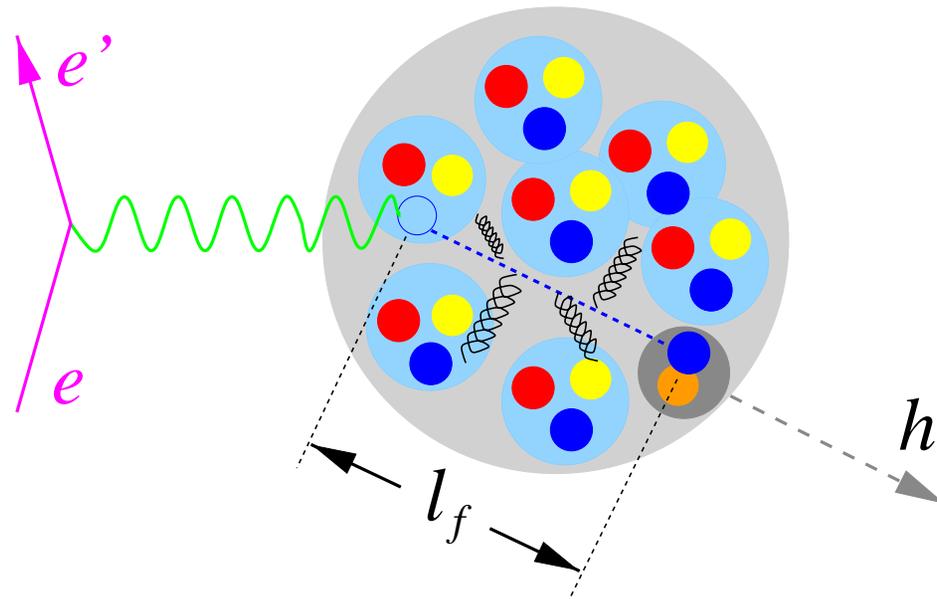
$$\sigma \sim \sum_f e_f^2 q_f(x) D_f^h(z)$$

- $q_f(x)$ = parton distribution function
- $D_f^h(z)$ = fragmentation function
- $x = Q^2/2m\nu$ – momentum fraction of struck quark
- $z = E_h/\nu$ – fraction of virtual photon energy transferred to hadron

Leptoproduction Kinematics



Hadron Electro-Production in Nuclei



- Hadron production from nuclei can be influenced by
 - Pre-hadronized **quark** interactions with extra nucleons in nucleus
 - Produced **hadron** interactions with spectator nucleons
- $\tau_f = l_f/c$, hadron formation time will affect which dominates

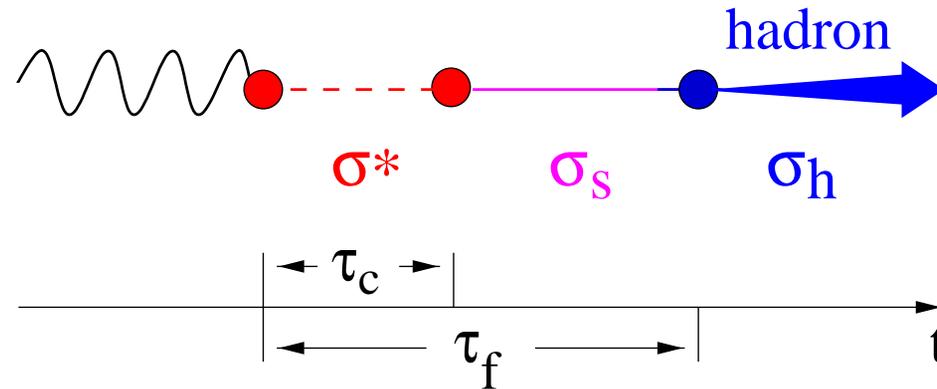
Definition of Attenuation Ratio

$$R_A(z, \nu) = \frac{\left(\frac{1}{\sigma} \frac{d\sigma}{dzd\nu}\right)_A}{\left(\frac{1}{\sigma} \frac{d\sigma}{dzd\nu}\right)_D} = \frac{\left(\frac{1}{N_e} \frac{dN_h}{dzd\nu}\right)_A}{\left(\frac{1}{N_e} \frac{dN_h}{dzd\nu}\right)_D}$$

where

$$\frac{1}{N_e} \frac{dN_h}{dzd\nu} \approx \frac{\sum_f e_f^2 q_f(x) D_f^h(z)}{\sum_f e_f^2 q_f(x)}$$

Models of Hadron Attenuation - Two Time-Scale Models



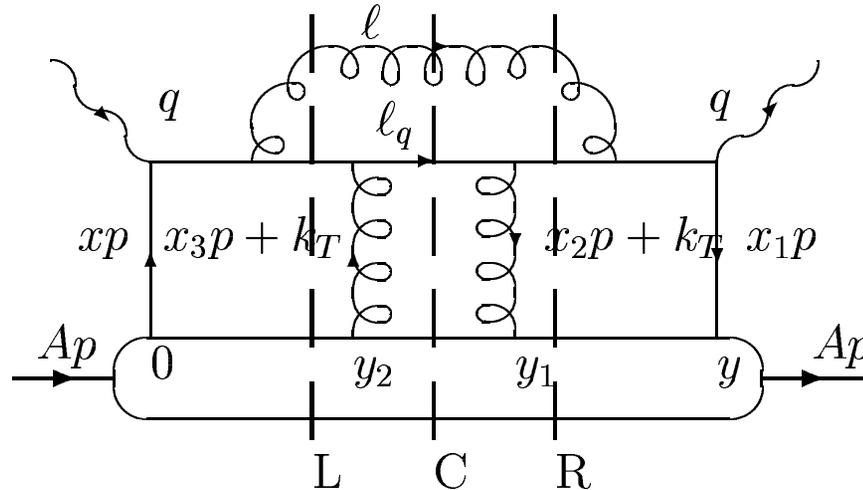
- Two time-scale (string) model – some hadronic constituents formed earlier than others and may interact with the nucleus

$$\tau_f - \tau_c = c \frac{E_h}{\kappa}$$

where κ is the string constant, $\kappa \approx 1 \text{ GeV/fm}$

- B. Kopeliovich et al.: hep-ph/9511214, NPA 740 (2004) 211.
 - Gluon Bremsstrahlung - Nuclear Suppression plus medium enhanced gluon radiation
- A. Accardi et al.: NPA 720 (2003) 131.
 - Rescaling of PDF and FF plus in medium absorption
- T. Falter et al.: PLB 594 (2004) 61; nucl-th/0406023 (PRC in press).
 - Prehadronic FSI with coupled channel treatment

Models of Hadron Attenuation with Partonic Interactions

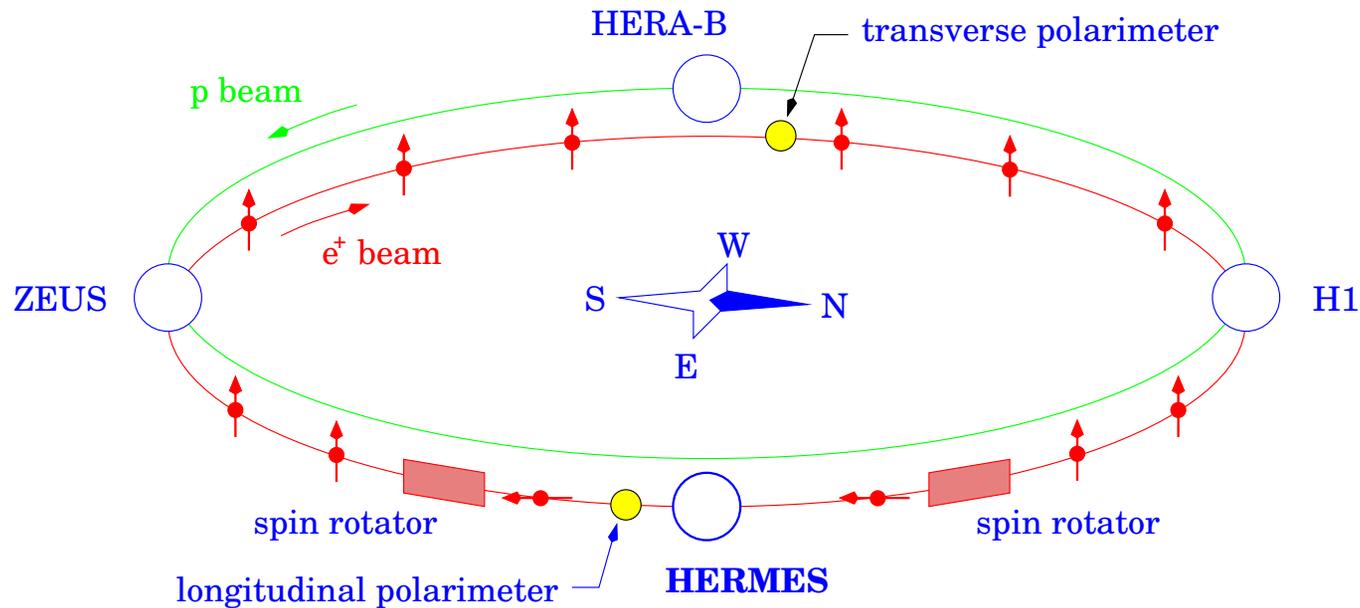


- Fragmentation functions are modified via quark rescattering with partons in other nucleons (higher-twist effects)
- Significant contribution from term involving gluon radiation and rescattering with gluon from other parton
- X.N. Wang et al.: PRL 89 (2002) 162301.
- F. Arleo et al.: EPJ C30 (2003) 213.

The HERMES Collaboration

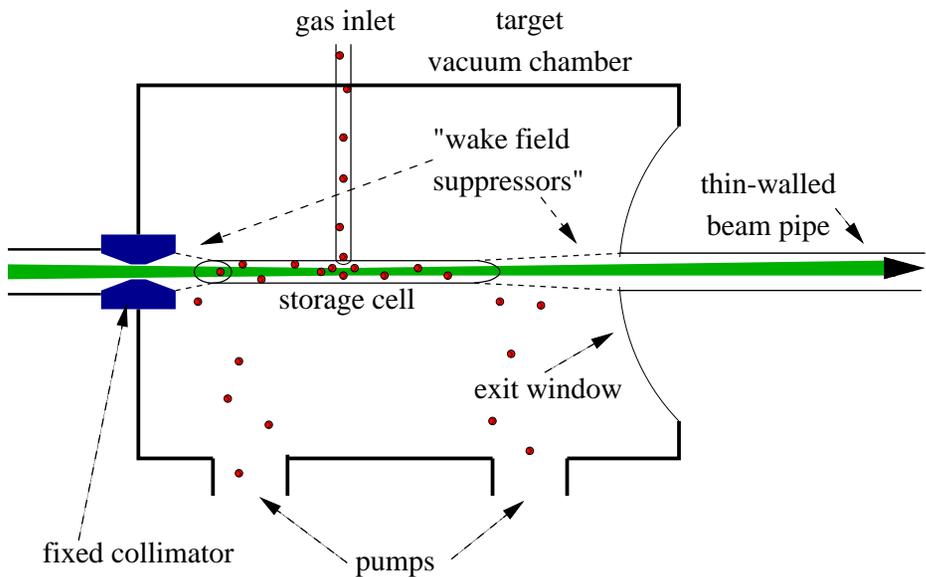
- Experiment located at DESY in Hamburg, Germany
- Members Institutions from: Armenia, Belgium, Canada, China, Germany, Italy, Japan, Netherlands, Poland, Russia, UK, and USA
- Homepage: <http://www-hermes.desy.de>
- Run/target History:
 - 1995: Commissioning/ Polarized ^3He
 - 1996/97: Polarized ^1H , Unpolarized ^1H , ^2H , ^3He , ^{14}N
 - 1998/99: Polarized ^2H , +RICH and Charm Upgrades
 - 2000: Polarized ^2H , Unpolarized ^1H , ^2H , ^4He , ^{20}Ne , ^{84}Kr
 - 2002-04: Polarized ^1H , Unpolarized ^1H , ^2H , ^{84}Kr

The HERMES Experiment



- The HERMES experiment at HERA/DESY
- Positron and electron beams of 27.5 GeV (12 GeV)
- Average Current ≈ 30 mA
- $\langle \text{Beam Polarization} \rangle \approx 50\%$

The HERMES Internal Gas Target



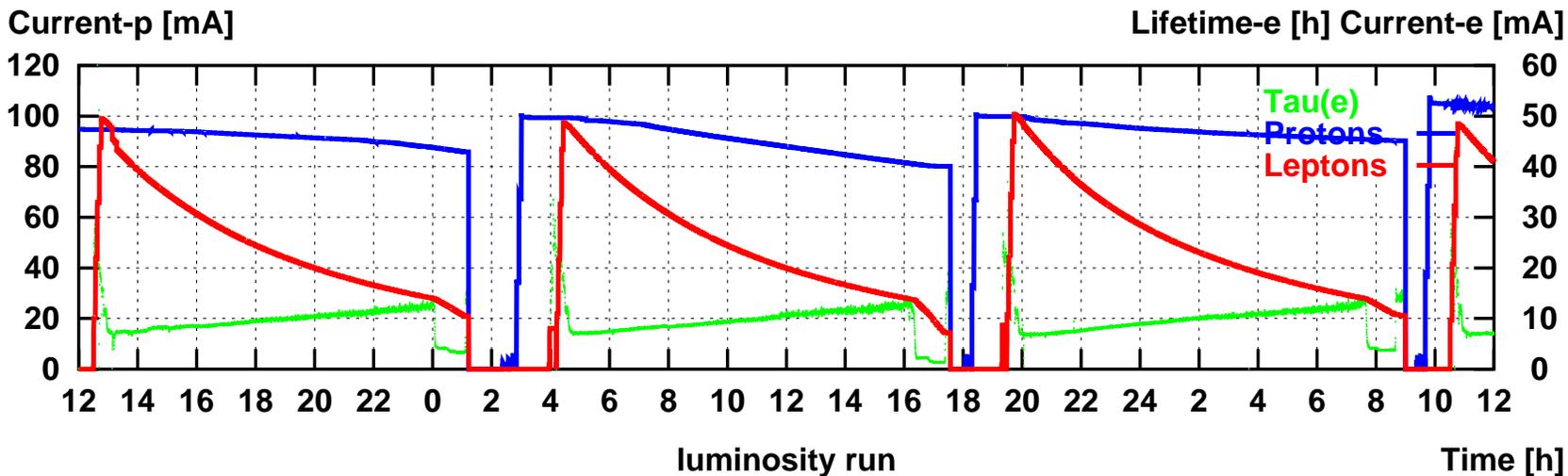
- $\langle \text{Target Thickness} \rangle \approx 10^{13} - 10^{15} \text{ atoms/cm}^2$
- High Density End-of-Fill Running

Fri Jul 14 12:00 2000

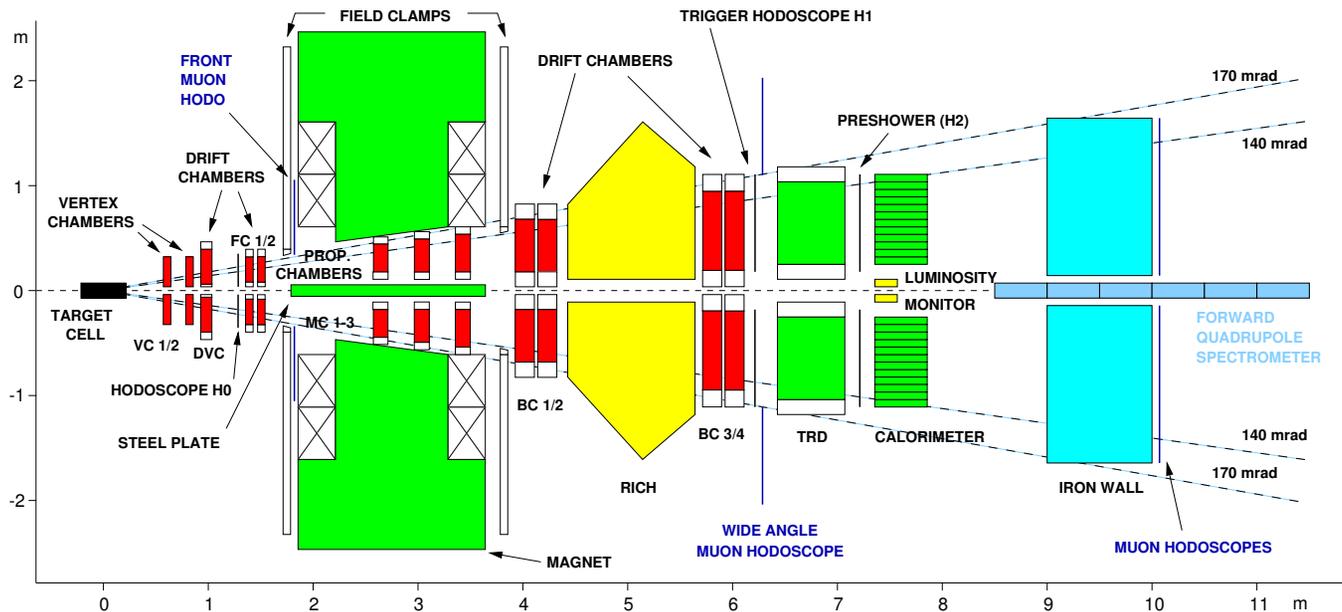
HERA

Sun Jul 16 12:00 2000

p: 103.6 [mA] -1.0 [h] 920 [GeV/c] e+: 41.0 [mA] 6.9 [h] 27.6 [GeV/c]

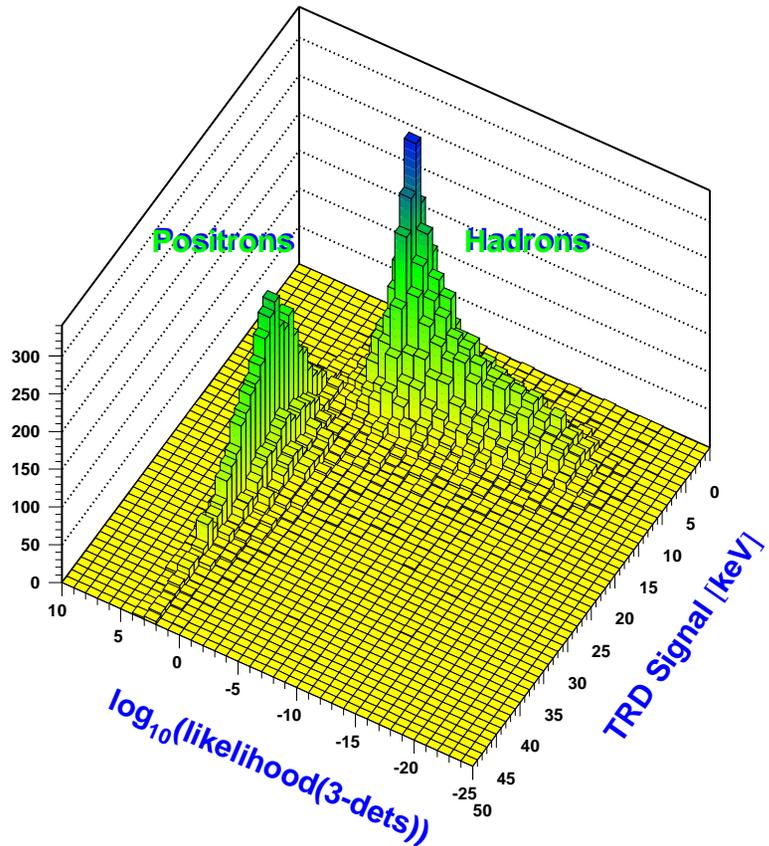


The HERMES Spectrometer

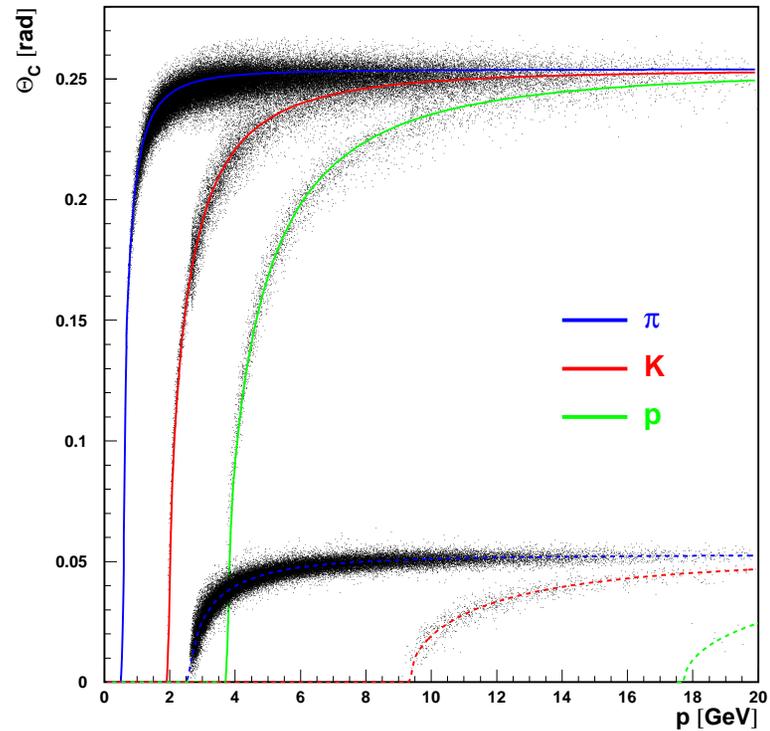


- Acceptance: $|\theta_x| < 170$ mrad, $40 < \theta_y < 140$ mrad
- Momentum resolution $\sim 1\%$ from 1 to 27 GeV
- Hadron/lepton contamination $< 1\%$ (with high efficiency)
- π^0 detection with EM Calorimeter
- Pre-1998: π identification from 4 to 13.5 GeV with threshold Cerenkov
- After 1998: Hadron identification with Dual Radiator RICH (allows $\pi/K/p$ separation from 2.5 to 15 GeV/c)

Particle Identification

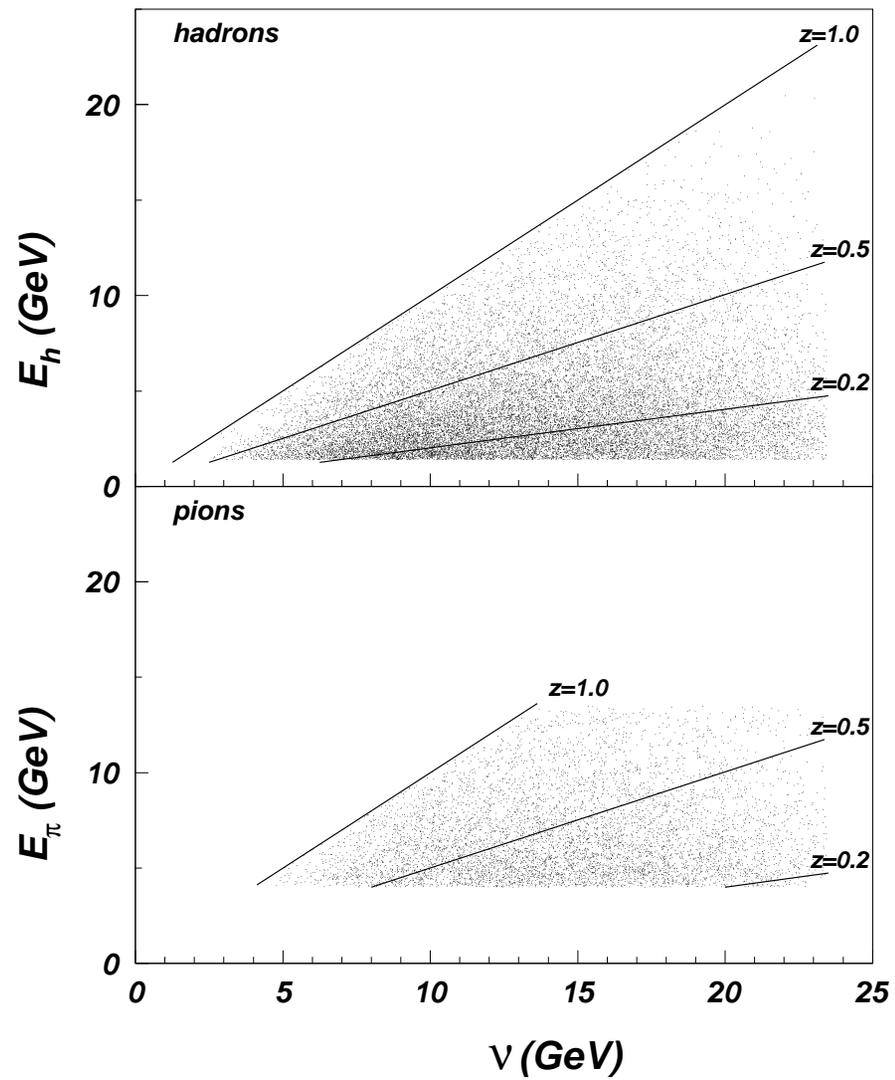


- Electron-hadron Separation



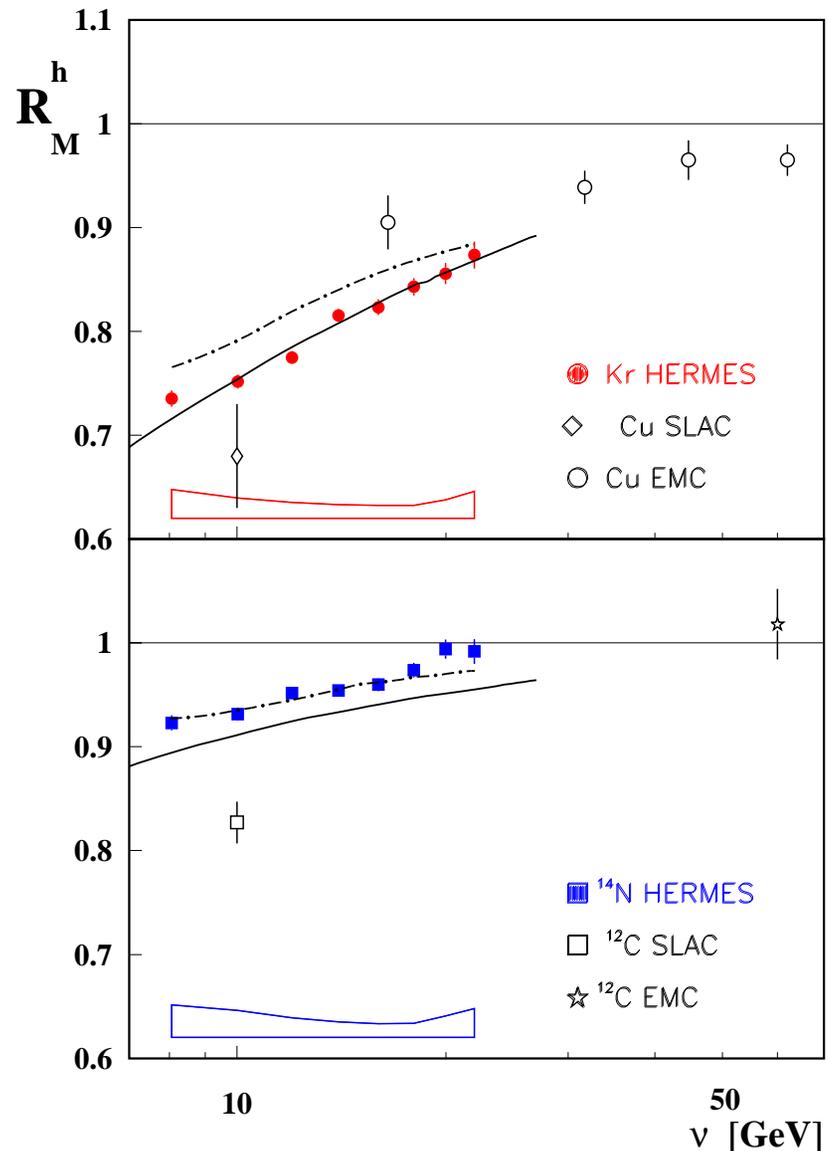
- RICH Detection Efficiency:
 π^\pm - 99%, K^\pm - 90%, p - 85-95%

Energy vs z for HERMES Experiment

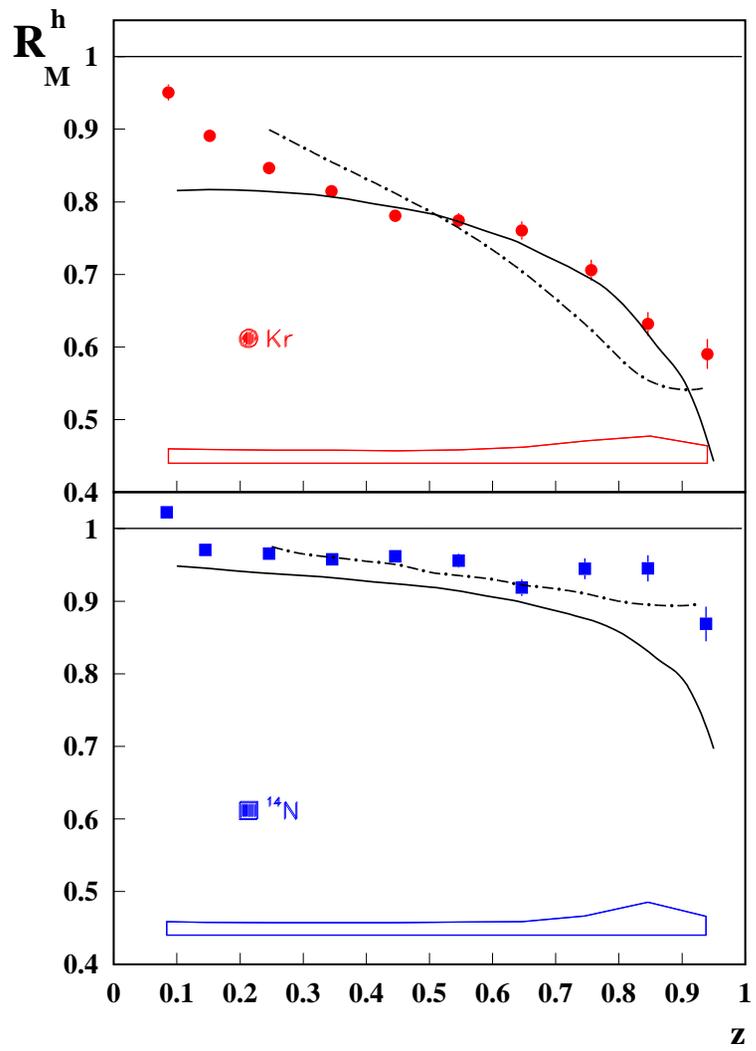


Hadron Attenuation vs. ν

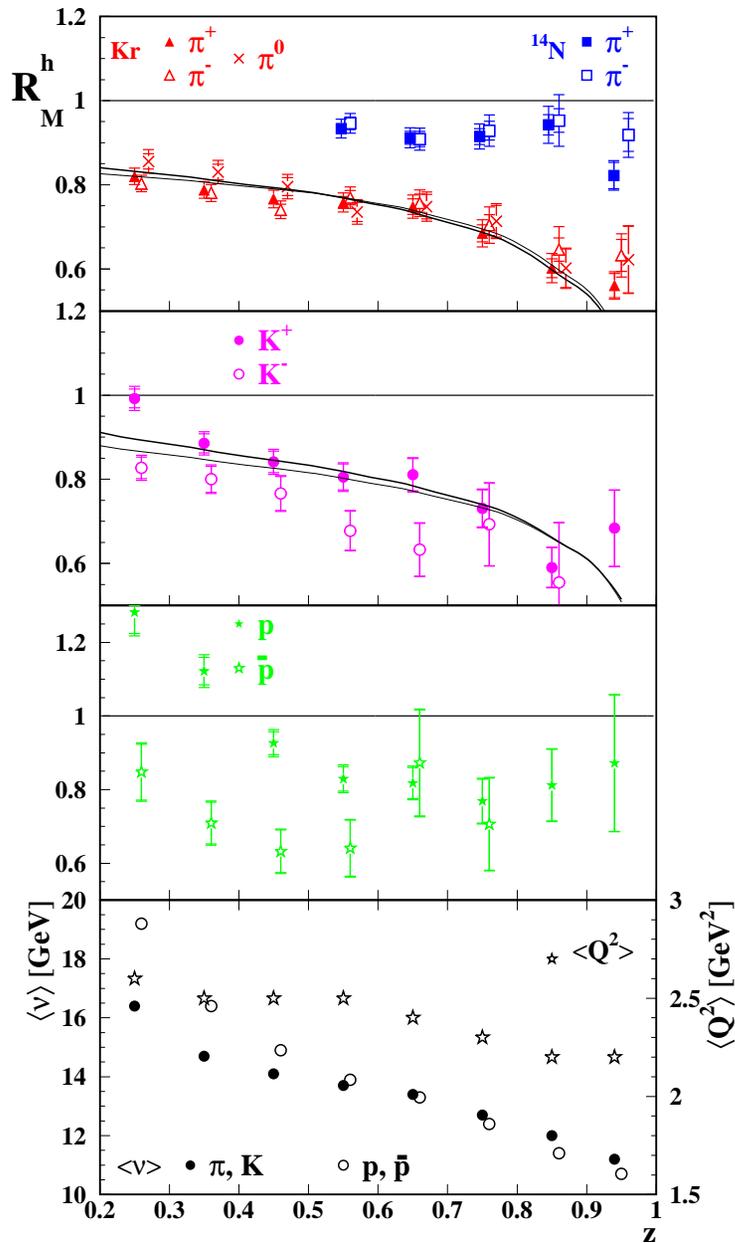
- Clear evidence for attenuation with ν dependence consistent among experiments
- At large ν , $R \rightarrow 1$ – hadron formation outside nucleus
- Solid curve - FF Rescaling + Prehadron absorption + hadron mult scatt (Accardi et al.)
- Dot-dash curve - pQCD (twist 4) modification of quark fragmentation (Wang et al.)
- HERMES, PLB 577 (2003) 37; EMC, Z.Phys C52 (1991) 1; SLAC PRL 40 (1978) 1624.



Hadron Attenuation vs. z



Hadron Type Dependence: ν Dependence



- RICH allows separation of hadron species (^{84}Kr only)
- Protons are less attenuated than pions and kaons \rightarrow longer formation time?

$$\sigma_{\pi^\pm} \approx 25 \text{ mb}$$

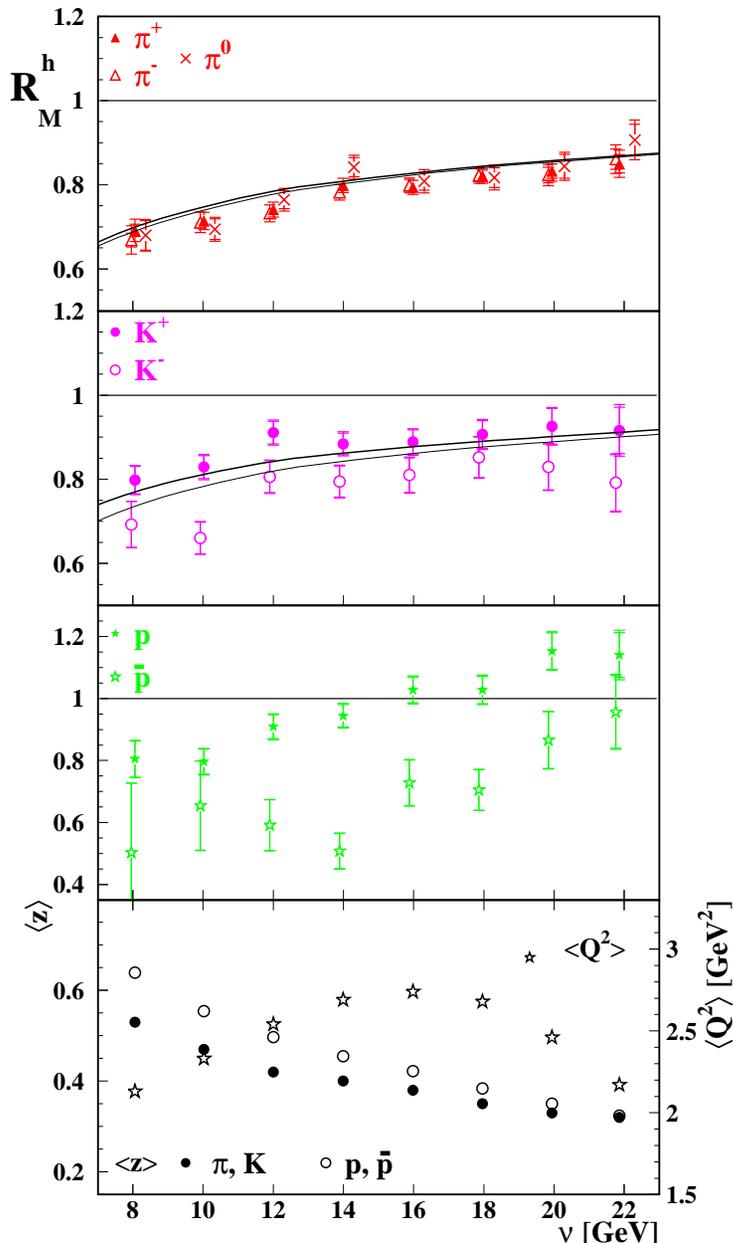
$$\sigma_{K^+} \approx 17 \text{ mb}$$

$$\sigma_p \approx 40 \text{ mb}$$

$$\sigma_{K^-} \approx 23 \text{ mb}$$

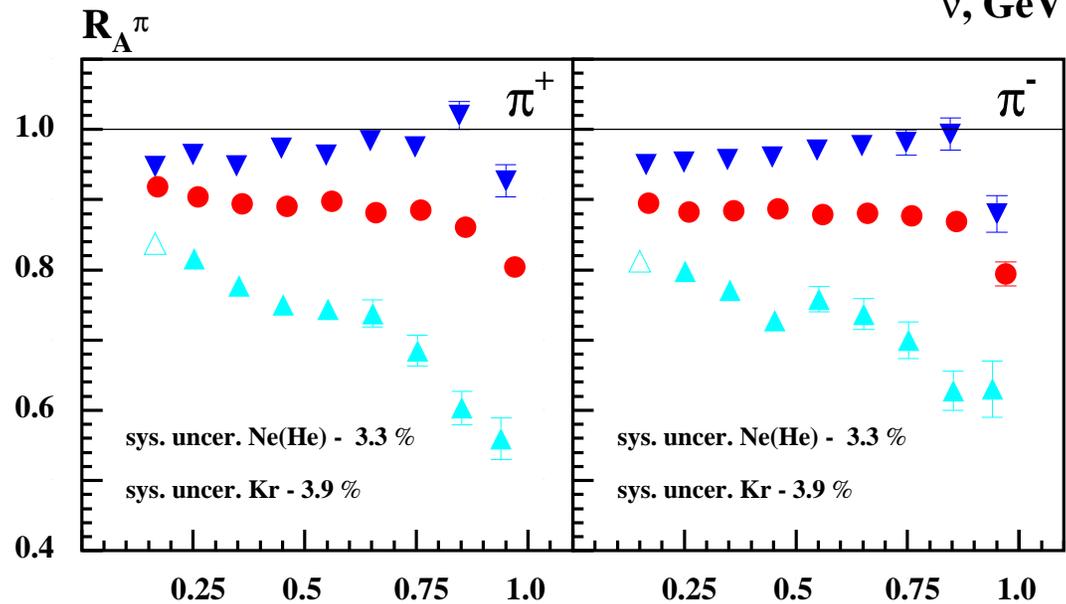
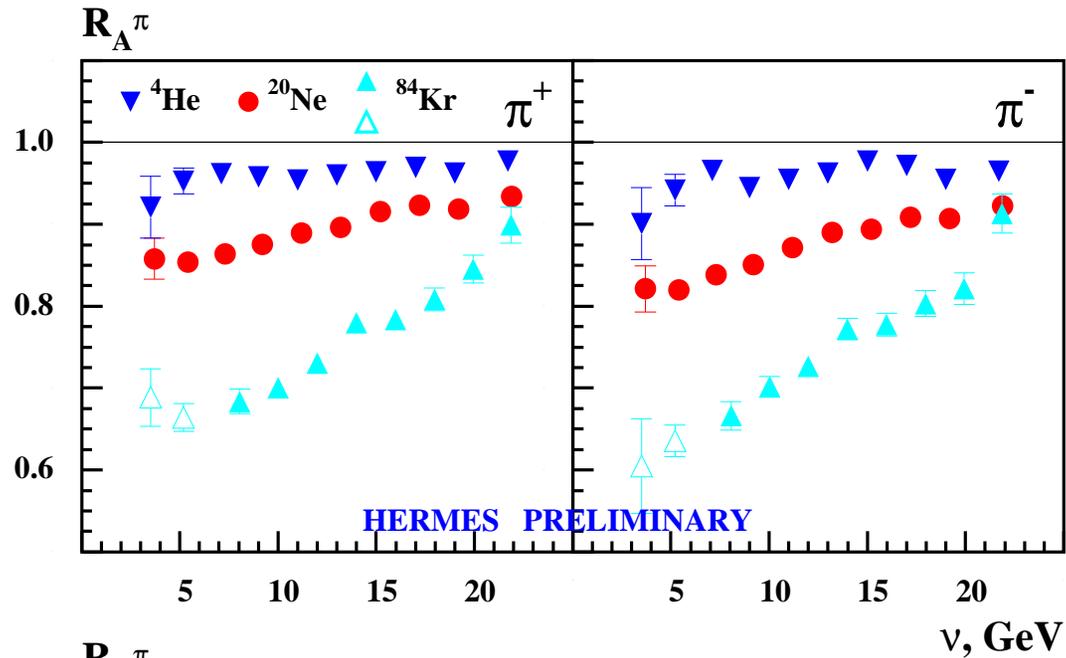
$$\sigma_{\bar{p}} \approx 60 \text{ mb}$$

Hadron Type Dependence: z Dependence

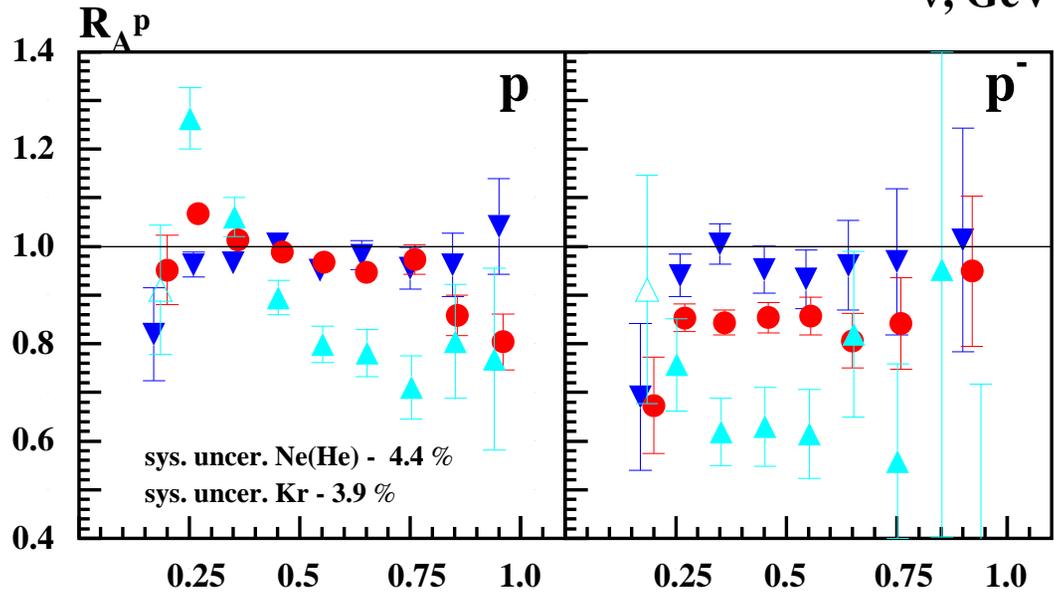
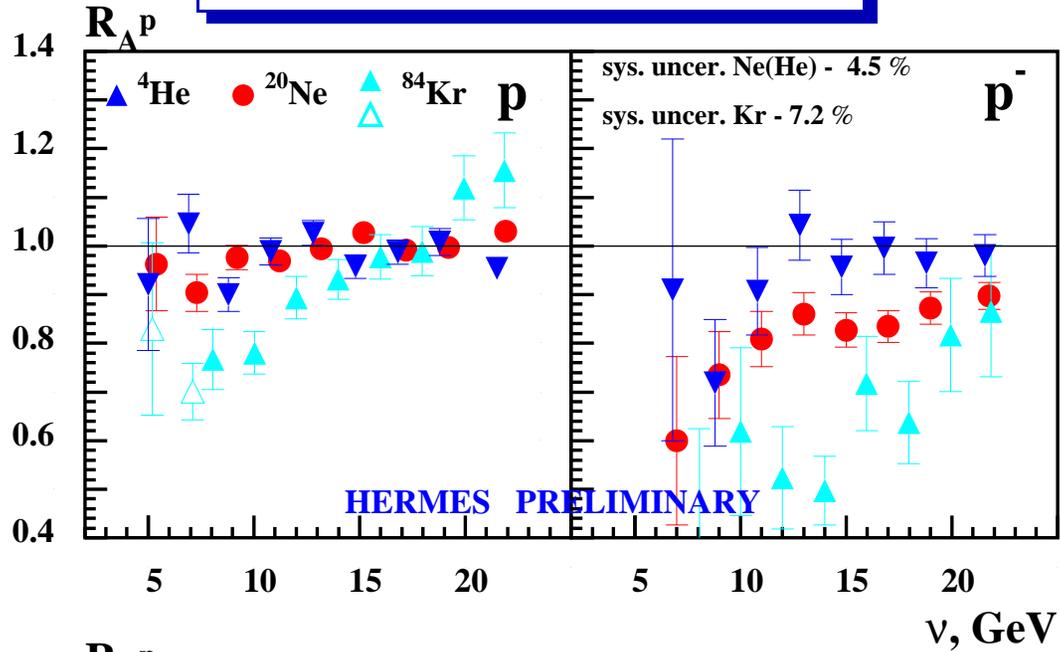


- At large momentum $\sigma_{\bar{p}} \approx 1.5 \sigma_p$
- Momentum range = 4–15 GeV
- At lower momenta anti-proton annihilation becomes more significant \rightarrow may explain difference between proton and anti-proton attenuation

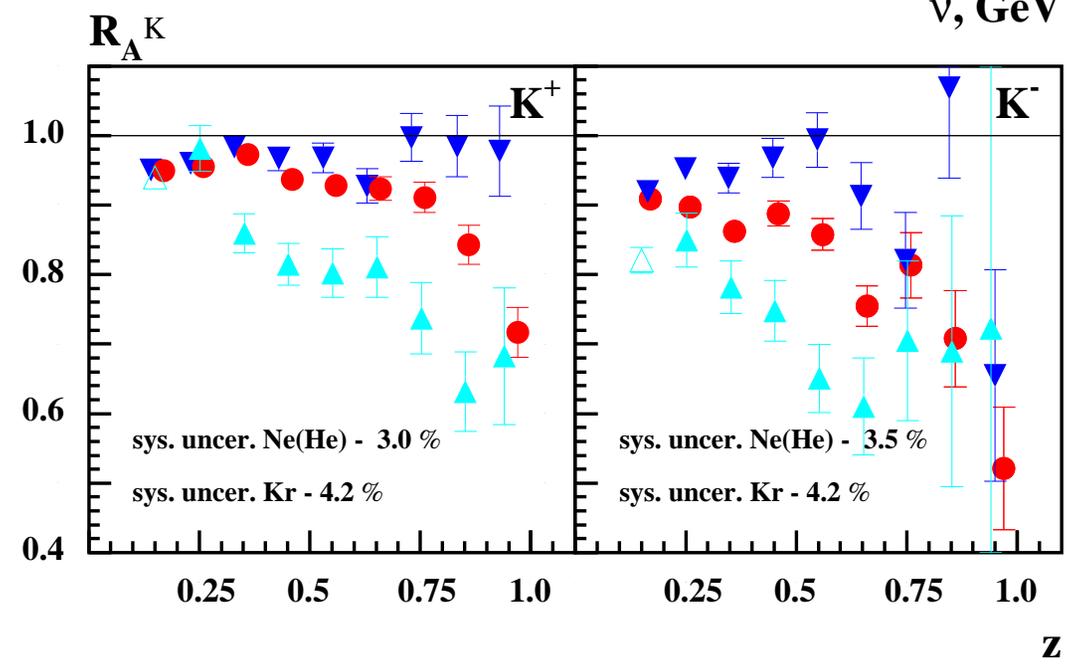
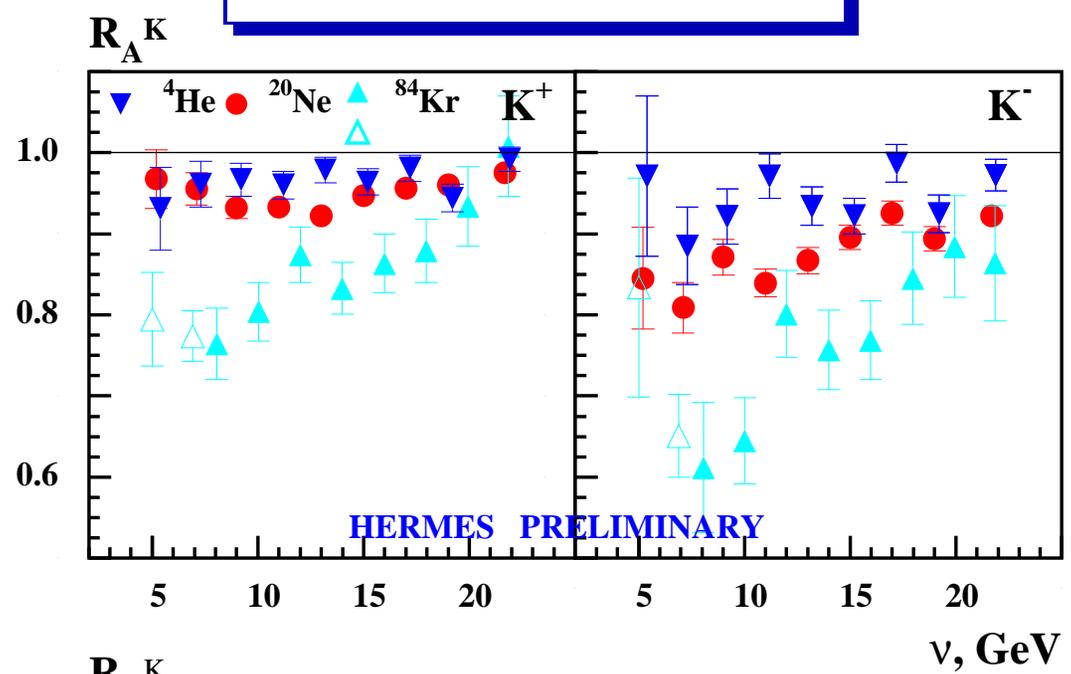
Charged Pion Attenuation



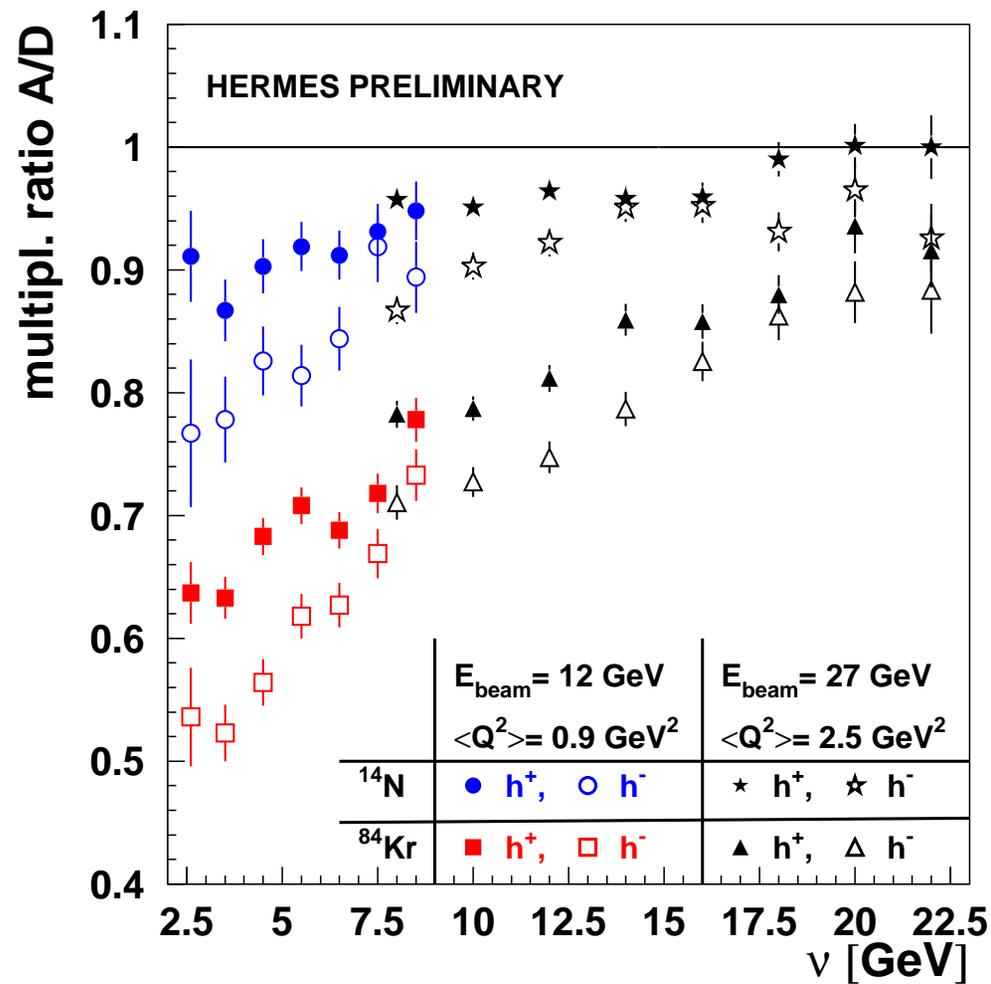
Proton Attenuation



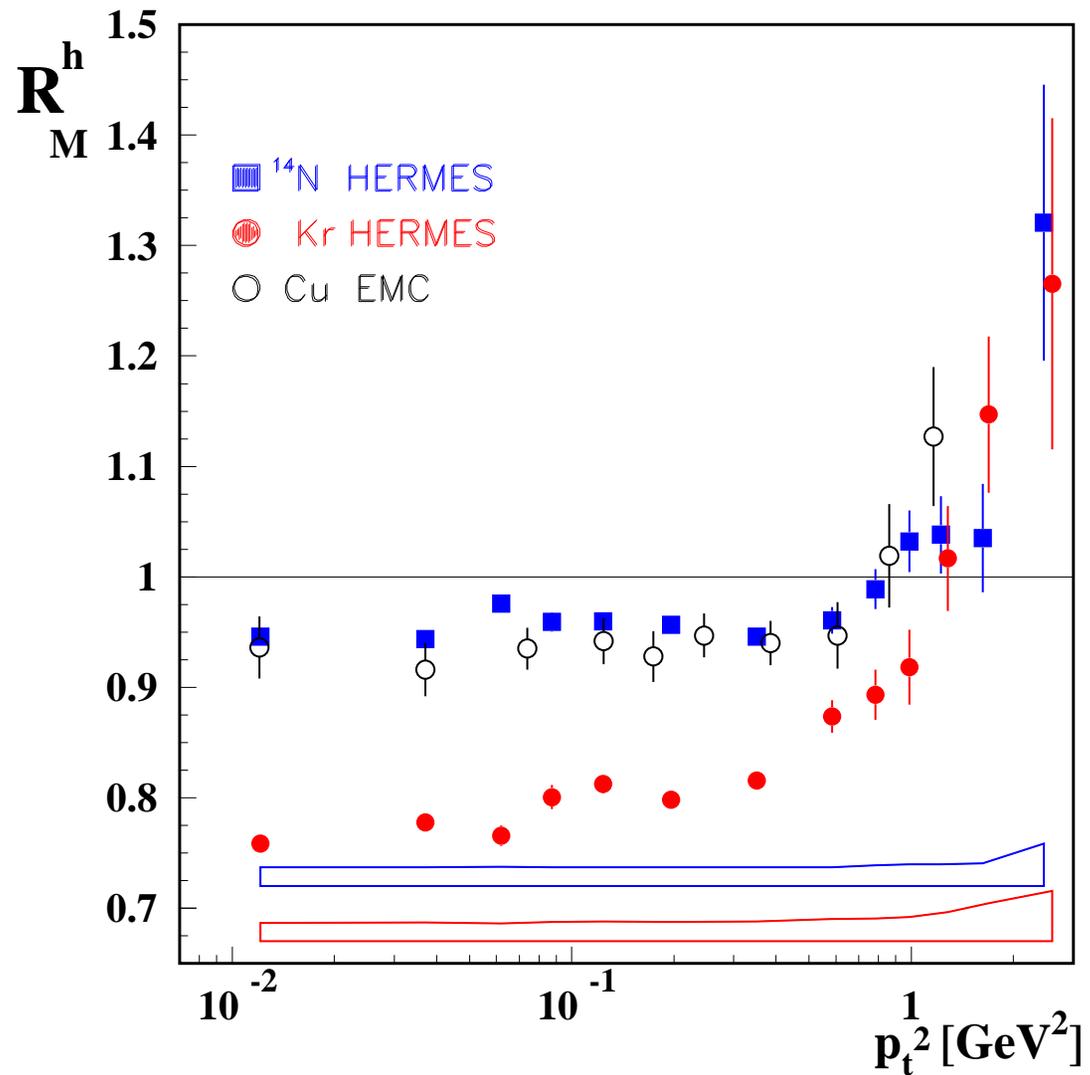
Kaon Attenuation



Comparison of 12 GeV Attenuation to 27 GeV

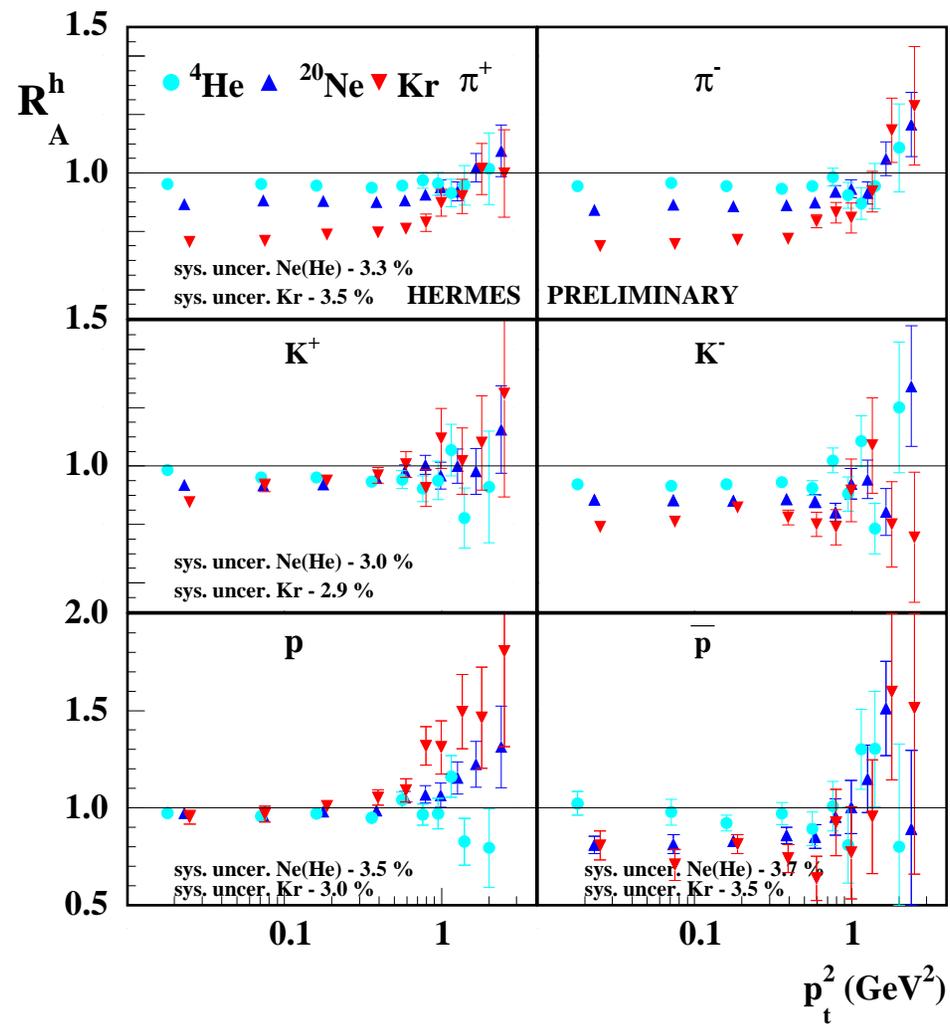


P_t Dependence



- Similar to pA observations of high p_t particle production

P_t Dependence for Identified Hadrons



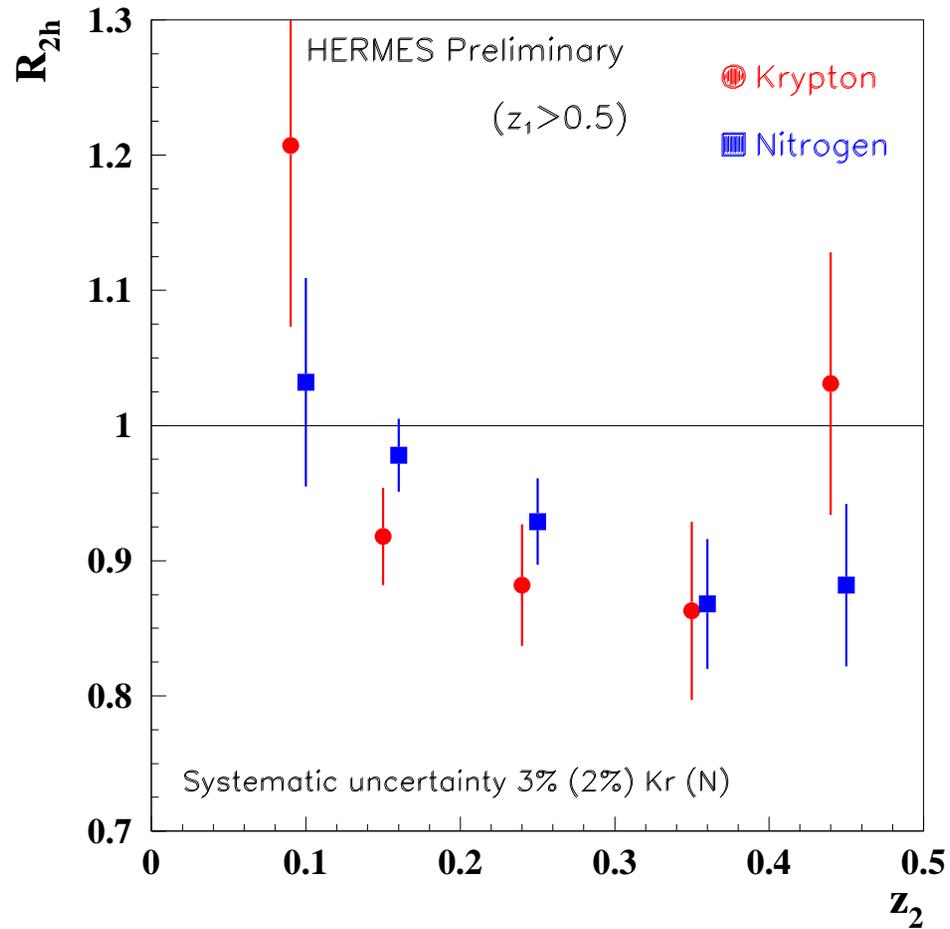
- Effect appears larger for protons

Two-hadron Production

$$R_A(z_2) = \frac{\left(\frac{d^2 N_{2h}(z_1 > 0.5, z_2)}{dN(z_1)} \right)_A}{\left(\frac{d^2 N_{2h}(z_1 > 0.5, z_2)}{dN(z_1)} \right)_D}$$

- If only hadronic effect: double-hadron over single-hadron ratio is expected to be much smaller in nucleus compared to deuterium.
- If only partonic effect: double-hadron over single-hadron ratio of nucleus over deuterium should be near unity.

Two-hadron Production



- Apparently small effect, with small A-dependence
- Described by Falter et al. with pre-hadronic FSI and transport code

Summary and Outlook

- HERMES data on hadron production span wide kinematic range and moderate A range, with identified hadron species
- Several models can describing attenuation of semi-inclusive hadron production in nuclei. Standard ingredients are
 - Nuclear Modification of the quark fragmentation functions
 - Prehadronization and final hadronization time scales
 - Partonic energy loss and scattering
- Comparison with RHIC d-AU results should be a good test for models
- New measurements with ^{131}Xe expected soon from HERMES
- Program at JLab in progress! (See talk of A. Brüll)